The Near-Earth Object Program Office at the NASA/Jet Propulsion Laboratory

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1. THE NEO PROGRAM OFFICE

As a result of the increasing public interest in comets and asteroids that can closely approach the Earth, NASA Headquarters established its Near-Earth Object Program Office at the Jet Propulsion Laboratory (JPL) in the Fall of 1998. Donald Yeomans was appointed Manager of this Office and he reports directly to Tom Morgan at NASA Headquarters (NASA HQ). At JPL, Yeomans works with Alan Chamberlin, Steve Chesley, Paul Chodas and Jon Giorgini, four recognized authorities on the orbital behavior of Near-Earth Objects (NEOs) and Ron Baalke, the NEO Program Office webmaster. Program Office personnel are active within the International Astronomical Union's Working Group for Near-Earth Objects and within the Technical Committee of this Working Group. This Technical Committee is charged with verifying predictions made by any international researcher that purport to show a non-negligible Earth impact in the future.

One of the primary objectives of the entire NEO program within NASA is the achievement of the so-called Spaceguard Survey Goal. This goal is to discover 90 percent of those NEOs larger than one kilometer within 10 years. This 10-year time interval is generally considered to have started in 1998 when Carl Pilcher articulated this goal before the House Subcommittee on Space and Aeronautics. The initial Charter for the Program Office carefully outlined its responsibilities with regard to NEOs along with those remaining with NASA Headquarters.

An actual impact by a large NEO is a very low probability event. However, there will continue to be cases in which specific predictions will be made of modest probability impacts at fixed future dates. News reports of these predictions may cause public concern even if the probability of impact drops to zero as additional observations are included in the computations. Formal communications pathways have not yet been established between NASA and other agencies and organizations that would naturally be involved in steps to observe, characterize, mitigate or handle emergency preparedness in the remote chance that such a prediction came to pass.

A great number of issues in this area remain to be addressed, but it is of prime importance that communication pathways and protocols be established to deal with the information about NEOs being gleaned daily through the active observations program being sponsored by NASA and carried out by researchers around the world. It is with this in mind that NASA Headquarters assigned JPL its role as the management center for the NEO Program Office in 1998. Its charter as elucidated by the Associate Administrator of NASA's Office of Space Science at that time, follows.

2. NEO PROGRAM OFFICE CHARTER AND RESPONSIBILITIES

The charter of the NEO Program Office is:

1) Coordinate ground-based observations in order to complete the survey

of Near-Earth Objects (NEOs), and to obtain accurate orbital elements for newly detected NEOs based on the best available data.

2) Facilitate communication both within the observing community and between the community and the public with respect to any potentially hazardous objects (PHOs) which are discovered as a result of the observational program and respond to public inquiries.

3) Establish, update, and maintain a catalog of NEOs together with an estimate of the quality of the orbital elements accessible to the scientific community and the public.

4) Develop and support a strategy and plan for the scientific exploration of NEOs including their discovery, recovery, ephemerides, characterization, in-situ investigation, and resource potential.

5) Support NASA HQ in coordinating with other government agencies and with foreign governments and international organizations on NEO issues.

NASA Headquarters Responsibilities for NEO Research Programs are as follows:

1) Solicit and select all science investigations, ground-based and space-based, for the detection and scientific exploration of NEOs.

2) Coordinate with other agencies and organizations including international agencies and organizations.

3) Assess the evolving understanding of NEOs which will result from the search and characterization effort in order to provide guidance for strategic planning and mission selection.

Communicating with the Media and Public

Scientists, scientific organizations and governmental entities have recognized and are in the midst of research efforts to characterize the threat to Earth posed by NEOs. Because these threats are, at the same time, low-probability and high-risk events, it is often difficult to communicate NEO issues properly to the public and media.

One of the key goals of the NEO Program Office is the effective communication of the general NEO risks to the public and media and the timely communication of specific NEO risks when warranted. This document addresses these communication issues.

3. THE NEAR EARTH OBJECT POPULATION

The Earth has been under a constant barrage of comets and asteroids since its formation some 4.6 billion years ago. Indeed, the very formation of the Earth was due to the agglomeration resulting from these impacts. Until about 3.8 billion years ago, the impact rate was intense and conditions on the proto-Earth were not conducive to the formation of life. However, once this early period of intense bombardment eased somewhat, asteroid and comet impacts may well have supplied the water and carbon-based materials that allowed the formation of life. The heavily cratered surfaces of Mercury, the moon, and any solar system body without a thick atmosphere to protect it, give testament to the continuous, on-going bombardment taking place within the solar system. While the Earth's atmosphere protects it from asteroids smaller than about 50 meters, the Earth has suffered a battering from larger comets and asteroids over geologic time scales. However, unlike our neighboring moon, Earth's wind and water erosion processes have filled in most of the resulting scars. Even so, over 150 impact craters up to over 200 km in diameter have been identified on the Earth's surface.

While the vast majority of asteroids reside between the orbits of Mars and Jupiter and almost all the comets are resident in the so-called Oort cloud one thousand times more distant than our outermost planet Pluto, a not insignificant fraction of these bodies reside in the Earth's neighborhood. Near-Earth asteroids (NEAs) and near-Earth comets make up the population of so-called near-Earth objects (NEOs). These NEOs are loosely defined as those comets and asteroids that approach the Sun to within 1.3 AU (astronomical units, a distance equivalent to the 150 million-kilometer, or 93 million mile, distance between the Earth and the Sun). Hence, they can either cross the Earth's orbit or approach it to within distances less than about 45 million kilometers. A sub-class of these NEOs is the so-called Potentially Hazardous Asteroids (PHAs). These are objects larger than about 150 meters whose orbits approach the Earth's orbit to within 0.05 AU (7.5 million kilometers). PHAs are so named because their orbits are close enough to Earth's that gravitational attractions by the planets could, over relatively short time scales, allow them to evolve into Earth crossing orbits – thus allowing the possibility of future collisions.

The Threat to Earth from Near-Earth Objects

The rate with which asteroids and comets run into the Earth strongly depends upon their size. For the very smallest dust and sand-sized particles, more than 100 tons of material hit Earth each day, while for objects large enough to threaten the continuation of civilization (1.5 km and larger), the average time between impacts is measured in hundreds of thousands of years. Although a number of near-Earth comets do exist, they represent only about 3 percent of the total population. However, because of their greater impact velocities, comets constitute more than 3% of the problem. Using information taken from the work by Chapman and Morrison (1994) and Toon et al. (1997), Table 1 outlines the impact intervals, energies and consequences for impactors of various diameters.

Table 1. Near-Earth Asteroids (NEAs)

NEA Diameter	Number of Objects Larger than Given Diameter	Typical Impact Interval (years)	Impact Energy (MT)	Crater Diameter (km)	Rough Estimates of Average Fatalities Per impact	Per year	Consequences of Impact Event
1 mm	Billions	Several daily		None	None	None	Sand grain sized particles from comets burn up in upper atmosphere causing meteors or shooting stars
10 m	150,000,000	5	0.065	None	None	None	Object will not likely survive passage through Earth's atmosphere.
50 m	2,000,000	200	8	1	4000	20	Severe airblasts. Objects of this size would be expected to pass within a lunar distance of Earth more than once a month..
100 m	300,000	3000	65	2	5000	5	Approximate size for stoney asteroid to survive atmospheric passage and impact Earth's surface. Local damage and loss of life if impact occurs on inhabited areas. Tsunamis inundate coastal regions a kilometer or so inland.
300 m	25,000	50,000	1800	6	5×10^5	10	Significant local damage for land impacts. Ocean wide tsunamis for water impact.
1.5 km	1,000	500,000	2×10^5	30	1.5×10^9	3000	Significant damage within hundreds of kilometers of ground zero. An ocean impact would cause tsunamis with flooding of proximate coastal areas for tens of km.
10 km	few	10^8	6.5×10^7	200	6×10^9	60	Global earthquakes, tsunamis and fires. Smoke and dust cause global darkness. Severe multi-year impact winter.

As is evident from this Table, the average number of fatalities per year strongly peaks for those asteroid impactors 1.5 km or larger. Hence the current NASA efforts are directed toward finding the large NEAs. Because of the large uncertainties involved with calculations of this type, the information outlined in Table 1 can only be considered very approximate. Furthermore, it is important to note that the impact of a given Earth-threatening NEO is a natural disaster that can be predicted and many kinds of potential impacts could probably be mitigated, or even avoided altogether, using current technology.

Near-Earth Object Orbit Determination and Impact Predictions

Once a comet or asteroid is discovered and follow-up observations provided, a rough preliminary orbit can be computed. Because it acts as the central clearing house for asteroid and cometary observations, the Minor Planet Center in Cambridge Massachusetts determines a preliminary orbit and categorizes the object as a NEO, or perhaps even a PHA.

When a new object is placed into the PHA category, the NEO Program Office provides regular orbit and ephemeris updates as more and more observations become available. These updated orbits are then routinely integrated forward for one hundred years or more to note any future close Earth approaches. This PHA orbit update process takes place daily as incoming observations are made available by the Minor Planet Center. The orbital parameters of PHAs and the associated close Earth-approach information is then posted to the Program Office web site (http://neo.jpl.nasa.gov) under "Potentially Hazardous Asteroids." The PHA tables on the web site are updated daily as necessary.

These tables provide preliminary impact probabilities for any PHA that makes a future close Earth approach to within 0.1 AU. These future close Earth approaches can be ordered by the web page user in terms of their close approach distances or time. Special off-line Monte Carlo numerical integration techniques are used to examine the orbital behavior of those objects for which a non-negligible impact probability is determined. In simple terms, these Monte Carlo techniques can accurately map the thousands of possible orbit variations the object may follow in the future. These special numerical techniques are especially useful for those orbits that show chaotic behavior as a result of a short data interval (uncertain preliminary orbit) and/or repeated close planetary passes in the future.

In general, a significant impact probability for a certain PHA in the future is defined as a probability higher than that of the background level for PHAs of the same size hitting Earth between the current time and the predicted impact of the known object. This background level is defined as the mean terrestrial impact frequency averaged over long time intervals. For example, from Table 1 we note that the likelihood of a 300-meter PHA hitting Earth each year is about 1/50,000. Over a period of 50 years, this probability rises to 50 x 1/50,000 = 0.001. If an actual PHA of a 300- meter diameter is discovered to be on an Earth-threatening trajectory and an impact probability of 1/100 (0.01) is computed for an Earth encounter 50 years from now, then this would be a significant event, since the impact probability of the predicted event is 10 times higher than the background impact frequency for a PHA of 300 meters colliding with Earth within 50 years.

The Torino and Palermo Scales

The so-called Torino Scale arose as a result of a meeting of scientists attending the "International Monitoring Programs for Asteroid and Comet Threat" workshop held in Torino Italy on 1-4 June 1999 (Binzel, 2000). This one-dimensional scale is meant to facilitate the difficult problem of communicating the NEO risk issue to the public. Predicted impact events in the future are assigned an integer value between zero and 10 depending upon the likelihood of the impact together with the kinetic energy of the event if it should occur. The kinetic energy of an impact event, measured in megatons (MT) of TNT explosives is proportional to the mass of the incoming asteroid times the square of its velocity upon impact (1MT = 4.2×10^{15} Joules). For example, Torino scale zero events would include relatively certain impacts of small (20 meters), low-mass asteroids. These objects would likely collide with the Earth's atmosphere with a kinetic energy less than 1 MT and would not be expected to be of much consequence because they would disintegrate in the Earth's atmosphere before reaching the surface. Torino scale zero events would also include a prediction of a potential future impact by a very large, kilometer-scale asteroid which has a very small chance of occurring (less than one chance in a million).

Since Earth impacts by sizable asteroids are extremely unlikely, almost all Earth close approaches by asteroids will receive a Torino Scale zero rating. Torino scale 1 events correspond to collision probabilities that are comparable to the current annual chance of an unknown object of the same size hitting the Earth in the next year (the annual background level). Because newly discovered PHAs normally have only a few observations with which to fit an orbit, preliminary orbits can be very uncertain and it is quite possible for an object to start out as a Torino scale 1 object and evolve into a Torino scale zero event as more and more observations are processed in the orbital solutions. In the exceedingly unlikely event that an asteroid larger than 1.5 kilometers is found with a high collision probability, this encounter would receive a Torino scale 10, indicating a very serious global problem. The communication of a Torino scale value to the public or media must always be accompanied by the associated date of the encounter event and an explanation that the given value is subject to revision as new or improved observations become available. In almost every case of a prediction having a Torino Scale of one or larger, new observations will result in its Torino Scale value dropping to zero.

At a meeting held in Palermo Italy in June 2001, a more quantitative "Palermo Scale" was presented (Chesley et al., 2001) that is intended for facilitating communication between astronomers rather than to the public or media. This more complex scale characterizes impacts across all impact energies, probabilities and dates in a natural way and thus can guide specialists is assessing the computational and observational effort appropriate for a given situation.

Communicating Low-Probability, High-Consequence Risks

A modest-sized NEO of 1.5 kilometers has the potential to strike Earth with kinetic energy some 20 times the explosive force of the world's combined arsenals of nuclear weapons. From Table 1, we note that even a small asteroid of 50 meters would be expected to hit Earth every 200 years on average with an explosive force more than 500 times greater than the Hiroshima nuclear blast in 1945. Objects of this size routinely pass within a lunar distance of the Earth every three weeks or so and yet this type of risk is poorly understood by the public, the media, and even by most scientists. The combination of the extremely low impact probabilities and the catastrophic consequences is difficult to comprehend because an asteroid impact event is so far removed from our personal experience.

Table 2 lists the odds of any one person dying as a result of a number of consequences. NEO impact fatalities are comparable with airline disasters and far worse than many familiar types of events that are taken seriously such as tornadoes and earthquakes. Although over extremely long time intervals, asteroid and comet impacts on Earth would be expected to produce as many fatalities as airline crashes, not one fully documented death by a NEO impact has taken place in recorded history. It is understandable that we humans find it difficult to grasp the meaning of low probabilities that are beyond the range of our experience.

Even as recently as a decade ago, attempts to interest agencies in the NEO impact issue were met with indifference. The topic was often associated with the so-called "giggle factor" and it was difficult to even introduce the issue without fearing ridicule. However, the importance of impact events over geologic times scales can no longer be denied. It has only been within the past few decades that a scientific consensus has formed on the importance of impact events in the solar system's history and upon the development of life on Earth. The collisions of comet Shoemaker-Levy 9 with Jupiter in July 1994 highlighted the extraordinary power of impact events with many of the more than two dozen Jupiter impacts creating persistent atmospheric dust clouds larger than the Earth itself. The two blockbuster movies during the summer of 1998 (Deep Impact and Armageddon) also raised the public's awareness of the problem.

Table 2.

Lifetime Chances of Dying From Selective Causes Within USA

Motor Vehicle Accident	1 in 100
Homicide	1 in 300
Fire	1 in 800
Firearms Accident	1 in 2,500
Electrocution	1 in 5,000
Airplane Crash	1 in 20,000
Asteroid/Comet Impact	1 in 20,000
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous bite or sting	1 in 100,000
Earthquake	1 in 150,000

Communicating the NEO Risk Issue to the Public and Media

The communication of an announcement of a potential threat by a near-Earth object to the public and the media would necessarily involve the International Astronomical Union (IAU), its Working Group on Near-Earth Objects (WGNEO), and the Technical Review Team of the WGNEO. The latter team has been charged with verifying Earth impact predictions made by any international researcher. Within the process by which such an announcement is made to the public and media, the following objectives seem appropriate:

1) To communicate the facts as they are known as effectively and accurately as possible and to do this in the most expeditious manner;
2) To ensure that the relevant information is reliable, the impact prediction is validated, and the results of this validation process are made public; and
3) To put into practice a policy of openness so as to counter possible accusations of secrecy.

4. THE NEO DISCOVERY PROCESS

The early efforts to discover NEOs relied upon the comparison of photographic films of the same region of the sky taken several minutes apart. The vast majority of the objects recorded upon these films were stars and galaxies and their images were located in the same relative positions on both photographic films. Because a moving NEO would be in a slightly different position on each photograph and the background stars and galaxies would not, the NEOs appeared to "rise" above the background stars when viewed with special stereo viewing microscopes.

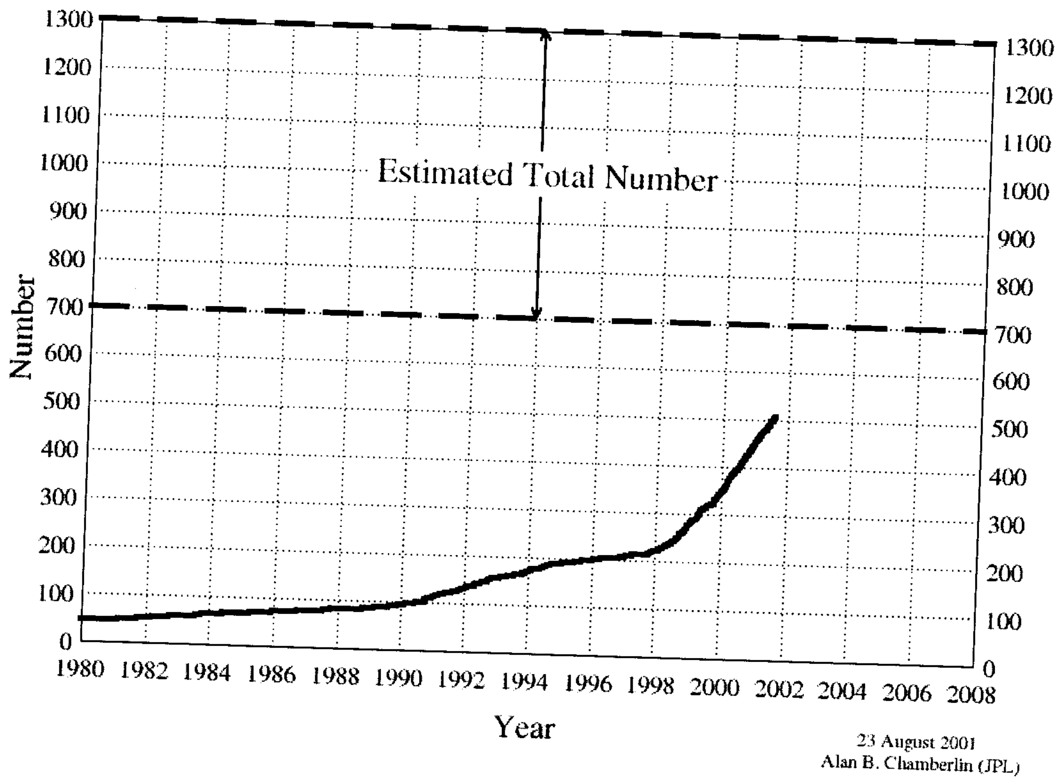
Nowadays, NEO discovery teams use charged couple devices (CCD) imaging systems rather than photographs. These CCD cameras are similar to those used in camcorders and they record images digitally in many electronic picture elements (pixels). The size of a CCD detector is usually given in terms of these pixels. A fairly common astronomical CCD detector might have dimensions of 4096 x 4096 pixels. While the CCD technology allows today's detectors to be more sensitive and accurate than the older photographic methods, the modern discovery technique itself is rather similar. Separated by several minutes, three or more CCD images are taken of the same region of the sky. These images are then compared to see if any objects have systematically moved to different positions on each of the separate images. For a newly discovered NEO, the separation of the object's location from one image to another, the direction it appears to be traveling, and its brightness, are helpful in identifying the object's proximity to the Earth, its size and its general orbital characteristics. For example, an object that appears to be moving very rapidly from one image to the next is almost certainly very close to the Earth. Sophisticated computer-aided analyses of the CCD images has replaced the older, manual stereo microscope techniques for all the current NEO search programs.

Not surprisingly, those discovery teams who search the largest amount of sky each month have the most success in finding new NEOs. How much sky each telescope covers per month will depend upon a number of factors including the number of clear nights available for observing, the sensitivity and efficiency of the CCD detector, and the field-of-view of the telescope. Wide field-of-view telescopes can cover more sky per given time than telescopes with narrower fields-of-view. It is also important for search teams to extend their searches to greater and greater distances from the Earth or, in other words, go to fainter and fainter limiting magnitudes.

NASA's NEO Discovery Goal

In terms of the discovery efforts for NEOs, NASA's current goal is to discover, within 10 years, at least 90 percent of all NEOs whose diameters are larger than 1 kilometer. To meet this so-called Spaceguard goal, the rate with which new objects are discovered will necessarily be largest in the first few years. This is because during the latter years of the 10-year interval, more and more detections will actually be of objects that have been previously found. Currently, the best estimate of the total population of NEOs larger than one kilometer is about 1,000 and number that has an uncertainty of about 300 in either direction (Rabinowitz et al., 2000; Bottke et al., 2000; D'Abramo et al., 2001). The progress toward meeting the Spaceguard goal can be monitored on the NEO Program Office web page (http://neo.jpl.nasa.gov) under "Number of NEOs" within the section on Near-Earth Objects. Figure 1 presents the progress to date in reaching the so-called Spaceguard Goal of find 90% of all NEAs larger than one kilometer within 10 years. Even though the current discoveries could be more than 50% of the total population of 1000, one would expect to find a disproportionate number of NEAs within the first few years of any survey.

Known Kilometer-Size Near-Earth Asteroids



NEO Discovery Teams

Currently, there are five NASA-supported search teams (LINEAR, NEAT, Spacewatch, LONEOS, Catalina) and one search team getting underway in Japan. Short descriptions of these search programs follow:

- **Lincoln Near-Earth Asteroid Research (LINEAR)**

Principal Investigator: Grant Stokes: (http://www.ll.mit.edu/LINEAR/)
In cooperation with the Air Force, MIT's Lincoln Laboratory currently is operating a near-Earth object discovery facility using two co-located one meter aperture GEODSS telescopes. GEODSS stands for Ground-based Electro-Optical Deep Space Surveillance and these wide field Air Force telescopes were designed to optically observe Earth orbital spacecraft. The GEODSS instruments used by the LINEAR program are located at the Lincoln Laboratory's experimental test site in Socorro, NM. Each LINEAR telescope has a two square degree field of view, a 1960 x 2560 CCD detector and each observes a patch of sky 5 times in one evening with most of the efforts going into searching along the ecliptic plane where most NEOs would be expected. The LINEAR program is responsible for roughly 70% of the current NEO discoveries.

- **Near-Earth Asteroid Tracking (NEAT)**

Principal Investigators: Eleanor F. Helin and Stephen Pravdo:

http://huey.jpl.nasa.gov/~spravdo/neat.html
The NEAT discovery team at the NASA/Jet Propulsion Laboratory also has a cooperative agreement with the U.S. Air Force to use an Air Force telescope to discover near-Earth Objects. The telescope aperture is 1.2 meters with a field of view of 1.2 x 1.6 degrees and the CCD camera format is 4096 x 4096 pixels. When used for NEO discovery efforts, Air Force contractor personnel operate the telescope and the data are routed directly to the Jet Propulsion Laboratory for analyses. In the Spring of 2001, the Oschin Schmidt telescope at Palomar mountain was brought on line to discover NEOs. Currently this 1.2 meter aperture instrument is operational with an effective field of view of 3.9 square degrees. Plans are underway to utilize, in 2002, a CCD mosaic camera provided by Yale University to increase the field of view to 9.4 square degrees. The NEAT program currently has NEO discovery programs operational in Hawaii and in southern California.

- **Spacewatch**

Principal Investigators: Bob McMillan and Tom Gehrels
http://pirlwww.lpl.arizona.edu/spacewatch/
Beginning in 1984, the 0.9-meter, Newtonian f/5 Steward Observatory Spacewatch telescope has been used full time for surveying comets and asteroids. The 0.9-meter telescope is used about 20 nights per month to search for near-Earth objects. The field of view is 2.9 square degrees with a 2048x2048 CCD detector. Each region of sky is scanned three times, about thirty minutes apart, to examine which objects have moved relative to the background stars. Spacewatch has discovered many of the smaller near-Earth objects that pass close to the Earth including a ten-meter sized asteroid (1994 XM1) that has the closest recorded Earth passage (105,000 km on Dec. 9, 1994). The Spacewatch group recently put into operation a 1.8-meter aperture telescope that has been designed to be a fast, wide-angle telescope (2.9 square degrees) suitable for going nearly a magnitude fainter than the 0.9 meter telescope.

- **Lowell Observatory Near-Earth Object Search (LONEOS)**

Principal Investigator: Edward Bowell
http://asteroid.lowell.edu/asteroid/loneos/loneos.html
Begun in 1993, the LONEOS system utilizes a 0.6-meter f/1.8 Schmidt telescope in Flagstaff Arizona to discover near-Earth comets and asteroids. The telescope was acquired from Ohio Weslayan University in 1990. Using a 4096 x 4096 CCD detector to cover a field of view of 2.9 x 2.9 degrees, the telescope is designed to make four scans per region over the entire accessible sky each month down to a limiting magnitude of about 19. In 2000, the efficiency of the LONEOS program in discovering NEOs increased significantly due to upgrades to the CCD camera and data reduction software.

- **Catalina Sky Survey**

Principal Investigator:Steven Larson
http://www.lpl.arizona.edu/css/

The Catalina Sky Survey (CSS) operates a 0.7-meter Schmidt telescope at Mt. Bigelow (20 km north of Tucson, AZ) for NEO search efforts. CSS also operates a 1.5-meter telescope at nearby Mt. Lemmon for following up NEO discoveries and providing the astrometric observations that are required to secure the orbits of recently discovered objects. The 0.7-meter Schmidt telescope has a field of view of 2.9 x 2.9 degrees and uses a camera equipped with a 4096 x 4096 CCD. Plans have been made to convert an existing 0.6-meter Schmidt telescope in Siding Spring, Australia into an efficient NEO discovery instrument. This Siding Spring Schmidt telescope would be the first full time NEO search program in the southern hemisphere. Robert McNaught has been using a 1-meter Cassegrain telescope at Siding Spring for follow-up astrometric observations a few nights per month in 1999-2001.

Japanese Spaceguard Association (JSGA)
Principal Investigator: Syuzo Isobe
http://pluto.mtk.nao.ac.jp/SGFJ/index-e.html
Japan's National Space Development Agency (NASDA), the National Aeronautic Laboratory, and the Space and Technology Agency have allocated the necessary funds to bring this facility on-line. This observatory is located near Bisei town, Japan. In addition to the search for NEOs, this facility will be used to track debris in Earth orbit. The 1-meter Cassegrain telescope has a field of view of 3 degrees and there are plans to use a mosaic of 10 CCD detectors each one of which will have dimensions of 2096 x 4096 pixels. A 0.5-meter telescope with a field of view of 2 x 2 degrees began operations in February 2000 and the 1-meter NEO search telescope began operations in late 2000.

NEO Follow-up and Physical Characterization Programs

The discovery of NEOs would mean little were it not for the follow-up observations that are used to refine their initial orbits and hence ensure their motions and positions will be predictable into the future. Several follow-up observing sites are operative internationally with many amateur astronomers taking an active and critically important role. Without their essential contributions, a recently discovered asteroid could easily be lost. Some of the efforts to characterize the NEO population using optical, infrared, and radar observations have been supported within NASA's R&A programs. In addition, several flight projects (see Table 3) designed to make close up comet and asteroid studies are either completed (NEAR-Shoemaker), already in progress (Stardust, DS1) or about to get underway (CONTOUR, Deep Impact, Rosetta, MUSES-C). The European Space Agency's Rosetta mission is planning to flyby two asteroids before effecting a rendezvous with comet Wirtanen in 2011. The combination of ground-based and space-based NEO characterization programs will provide critically important insights into the composition and structure of NEOs. In the unlikely event that a NEO is found on an Earth threatening trajectory, knowledge of its size, composition and structure would be necessary before a successful mitigation campaign could be undertaken.

Table 3. Missions to Comets and Asteroids (http://neo.jpl.nasa.gov/missions.html)

Mission	Bodies under study	Times of Investigation
Near-Earth Asteroid Rendezvous (NEAR-Shoemaker) (NASA)	Asteroids Mathilde and Eros	June 1997 & Feb. 2000- Feb. 2001
Deep Space 1 (DS1) (NASA)	Comet Borrelly	Sept. 2001
Comet Nucleus Tour (CONTOUR) (NASA)	Comets Encke & Schwassmann-Wachmann 3	Nov. 2003 & June 2006
Stardust (NASA)	Comet Wild 2	Jan. 2004
MUSES-C (Japan NASDA)	Near-Earth Asteroid	2004
Deep Impact (NASA)	Comet Tempel 1	July 2005
Rosetta (ESA)	Asteroid 4979 Otawara Asteroid 140 Siwa Comet Wirtanen	July 2006 July 2008 Nov. 2011

5. THE MITIGATION OF EARTH-THREATENING NEO'S

In conjunction with the passage of the 1990 NASA Multiyear Authorization Act, the Committee on Science, Space, and Technology of the House of Representatives directed NASA to design a comprehensive program for the detection of asteroids crossing the Earth's orbit, and to define systems for destroying or altering the paths of asteroids headed for Earth. In response, NASA undertook two workshops to evaluate the threat to the Earth from asteroid and comet impacts and to explore remedial actions that would prevent such disasters.

The first workshop sought to define the spectrum of threats and proposed the Spaceguard Survey (Morrison 1992) to greatly expand the knowledge base of these objects. The second (Interception) workshop was held in January 1992 at the Los Alamos National Laboratory in New Mexico (Rather and Rahe, 1992). Since these workshops were held, there has been considerable progress toward meeting the goals outlined in the Spaceguard Survey Report. Clearly, the first priority should be to discover most of the large NEOs and track their motions into the future to predict future Earth close approaches and impact probabilities. These international efforts are moving along well, with NASA taking the lead role. However, apart from the 1992 workshop on NEO interception, there has been very little additional work undertaken to study the mitigation aspects of near-Earth objects. In the introduction to the 1992 Interception report, it is stated that neither NASA nor the Department of Energy is responsible for formulating national policy regarding future deflection or destruction of near-Earth objects. As a result, there is apparently little in the way of national or international policy on this issue.

While there is a dearth of international policy dealing with the threat from NEOs, some technical studies have been carried out to explore the likely scenarios for deflecting or destroying Earth threatening NEOs. Some of the following discussion is based upon the work by Ahrens and Harris (1994). While any treatment of the mitigation of threatening NEOs is necessarily cursory and preliminary, there are a number of general conclusions that can be drawn. Assuming that the predicted Earth impact is several years in the future, the following conclusions can be made:

1. There is increasing evidence that some, perhaps most, asteroids are rubble pile structures or heavily fractured rocks. Before any mitigation of an Earth- threatening NEO is undertaken, the object's mass and structure would have to be understood. Deflection techniques would differ dramatically depending upon the nature of the NEO.

2. The more time available before the predicted impact, the easier the mitigation task. Given a few decades of warning time, current technology should be capable of deflecting even the largest NEOs.

3. In general, the most effective deflection technique would be to cause the threatening NEO to either lose or gain orbital energy. By applying a velocity impulse at perihelion in the direction of the NEO's orbital motion (or counter to it) with sufficient magnitude, the NEO's new trajectory could be altered to miss the Earth entirely. For example, a NEO headed for the Earth's center could be deflected by one Earth radius using a velocity change of only 7 mm/s if the NEO impulse were applied 10 years in advance.

4. For small, solid NEOs (diameters of about 100 meters or less), several mitigation techniques are available, including kinetic energy impacts. For example, consider the Deep Impact mission plans to send a 350 kilogram copper impactor into comet Tempel 1 in July 2005. Although the energy of this 10 km/second impact will shrink the orbit of the comet by only a few meters, the same impact on a much smaller NEO (diameter of about 100 meters) would be sufficient to deflect it one Earth radius in ten years time.

5. For small solid NEOs (diameters less than 100 meters), additional techniques that require landing on the NEO could also be used (e.g., mass drivers, solar sails, and rocket engines). However, these techniques would be far more complex and costly than kinetic-energy or explosive impactors since they would have to be fastened to the NEO's surface, operate over lengthy periods, and consideration would have to be made for the NEO's rotation characteristics. In addition, these landed options would require that the spacecraft successfully rendezvous and land on the NEO's surface – a far more difficult task than simply colliding with the threatening NEO.

6. For large, solid NEOs (with diameters of about 1 kilometer), deflection by kinetic-energy impactors would be untenable since over 10-year time scales, this technique would require an impactor mass of hundreds of tons. A high-velocity delivery of a surface or sub-surface nuclear weapons blast would be

expected to excavate significant ejecta, thus imparting the required impulse upon the NEO itself. This would not require a NEO rendezvous.

7. For solid NEOs and especially for NEOs with fragile rubble pile structures, care must be taken to keep the deflection velocity impulses less than the impulse necessary to break up the object (about equal to the object's escape velocity). A large NEO fractured into sizable chunks would be expected to cause more damage to Earth than the single, intact NEO.

8. For the largest of NEOs (diameters of about 10 kilometers), repeated nuclear surface or sub-surface blasts may be necessary. For large rubble pile NEOs, a buried nuclear charge may have to be used in an effort to disperse the object into fragments that would either miss the Earth entirely or be small enough that they would not be expected to survive penetration through the Earth's atmosphere.

It appears that the least complex mitigation techniques would include kinetic energy or nuclear blast impactors for small and large NEOs respectively. Most of the conclusions listed above apply for impact events that are predicted to occur several years into the future. It is very unlikely that a large, threatening NEO will escape detection long enough that only a few months' warning time remained before impact. Long-period comets, of course, are the wild cards in these analyses since they can be very large and not show themselves until their volatile ices begin to vaporize within the orbit of Jupiter. Thus, it is conceivable that large, long-period comets could be detected with only a few months' warning time. However, the number of these comets, compared to the number of near-Earth asteroids, is very small.

Hence, the major problem is with large, threatening near-Earth asteroids and the mitigation of these objects is, in general, possible using current technologies once an actual threat has been identified. It is true that there are several hundred thousand NEOs smaller than 1.5 kilometers, yet large enough to reach the Earth's surface, and the frequency with which they hit is far greater than the larger objects noted in the Spaceguard Goal. However, their impact effects would not be global, so that timely precautions and evacuations could dramatically reduce the damage if the object is discovered with sufficient advance warning. These smaller NEOs are being discovered currently and when the discovery efforts achieve the Spaceguard Goal, discovery systems could be optimized to find them more efficiently.

The cost and risk of a space-based defense system to deal with small threatening NEOs seems to be out of proportion to their threat and for the large NEOs, the likely long lead-time before impact would not require an active NEO defense system to be "at the ready." To establish a planetary defense program for NEOs would be far more costly than current ground-based search efforts and perhaps counterproductive. In addition to the restrictions placed upon nuclear weapons in space by international laws, the development and maintenance of a weapons-based NEO response program raises significant issues relating to accidents and misuse of these defenses. Nuclear defense systems designed to deflect threatening asteroids away from Earth could also be misused to deflect benign asteroids toward Earth. A reasonable approach to mitigation might include efforts to study and design the optimal strategies and techniques for different types of objects and time scales. In addition, we need to redouble our efforts to understand the compositions and structures of the NEO population. However, a prudent course of action for the mitigation of Earth-threatening NEOs would delay the building and deployment of any NEO interceptors until a true threat has been identified and verified.

As has been noted, the first and most important step in addressing the NEO problem is to discover the vast majority of the large NEOs and monitor their future motions. These activities are currently underway.

6. POLICIES AND RESPONSIBILITIES

Announcing NEO Event Discoveries

There are two possible scenarios for the discovery of a near-Earth object that has a non-negligible Earth impact probability and is, at the same time, large enough to cause a problem upon colliding with Earth (e.g., an event with Torino scale of 1 or higher).

1) The first scenario would involve a discovery, by personnel outside the NASA NEO Program Office, of a significant future NEO impact probability. In this case, Program Office personnel would be expected to assist in the collection of additional observations. As members of the Technical Review Team of the International Astronomical Union's (IAU) Working Group on NEOs, Program Office personnel would also be expected to help verify the impact probability calculations. In accordance with IAU procedures, an official announcement of a significant impact prediction would be first undertaken by the group discovering the event and/or by the IAU. In conjunction with such an announcement, Program Office personnel, in their role as NASA's expert group on NEOs, may wish to prepare appropriate background information relating to the discovery, which would be prepared for distribution to the media and public by the JPL Media Relations Office. Prior to release, such information would be reviewed and approved by NASA's Office of Space Science Public Affairs Officer.

2) The second scenario would involve the identification of a future NEO impact possibility by personnel of the NEO Program Office. The first step in the verification process would be to collect all available observations and provide an up-to-date prediction and then submit the calculations and existing observation set to the IAU NEO Technical Review Team for verification. This information would also be sent to the chair of the IAU Working Group for Near-Earth Objects, the President of IAU Division III, and the General Secretary of the IAU. The IAU

NEO Technical Review Team would be expected to finish their work within 72 hours.

Once the calculations have been verified, NEO Program Office personnel would be expected to seek additional observations in the archives that might further improve the orbital calculations. Each case should be assessed systematically, carefully listing points against and in favor of a public announcement. If there is a clear case for a delay of up to several days for reasons that can be set out and defended, then such a delay will be undertaken. A draft statement announcing the discovery will be prepared by the JPL Media Relations Office in cooperation with the NEO Program Office, and delivered for review, comment and approval to NASA's Office of Space Science Public Affairs Officer in preparation for possible release to the media and public.

News Release and Public Information Policy and Procedures

It is the responsibility of the Media Relations Office to ensure that any NEO announcements contain appropriate caveats and other explanatory language to place the discovery in proper context and to minimize the chance that the new information is misinterpreted as alarmist.

Timing, Contact Information and Distribution of NEO News

Any future announcements of close Earth-approaching NEOs by NASA NEO Program Office personnel should be guided by the following:

a) The timing of any announcement should be judged according to individual circumstances while having due regard for the ideal of openness, timeliness, and the availability of expert personnel to respond to inquiries.

b) An announcement should be in the form of a widely circulated notice for the news media, or a statement and supplementary material for the news media, prepared by the Media Relations Office for the NEO Program Office.

c) As with other JPL and NASA news materials, points of contact with telephone numbers shall be included; for announcements falling on a Friday, weekend or holiday, appropriate weekend telephone contact numbers will be made available.

Summary

As is evident from Figure 1, the last few years have witnessed considerable progress toward meeting the so-called Spaceguard Goal of discovering 90% of the NEOs larger than one kilometer within ten years. If the total population of NEOs larger than one kilometer is 1000, we are more than half way toward meeting this goal. However, because the discovery rate of new NEOs will be disproportionately higher during the first few years of the survey, there is reason to believe that the current discovery rate is not sufficient to allow the Spaceguard

Goal to be achieved by 2008. Activities underway to increase the NEO discovery rate include the following recent developments:

- October 1999: The LINEAR team began using a second one meter Air Force telescope to increase their discovery rate. LINEAR also has plans to utilize a 0.5 meter telescope to assist in the follow up observations necessary to secure the orbits of recently discovered NEOs.
- March 2001: NEAT brought on line a 1.2 meter wide field telescope at Palomar Mountain for automated NEO discovery. In 2002, a CCD mosaic camera, provided by Yale University, will allow the Palomar NEAT telescope to more than double its current field of view. NEAT also receives NEO discovery data from an ongoing 1.2 telescope which is owned and operated by the Air force on Maui Hawaii.
- May 2001: The recently operational Spacewatch 1.8 meter telescope discovers its first potentially hazardous object. Spacewatch currently operates both their 1.8 meter and 0.9 meter telescopes near Tucson Arizona.
- October 2001: The Japanese Spaceguard center will inaugurate a new NEO search telescope at the Bisei town observatory in Japan. This 1.0 meter telescope will join the 0.5 meter telescope which is already operational.
- Plans are underway to more closely coordinate the five NASA-supported NEO discovery programs. Currently, the sky areas searched during the previous night are posted for each of these search programs. The future goal will include a posting of future sky coverage plans and steps toward inter-program coordination so that simultaneous searches of the same sky area can be minimized.

Once discovered, the orbits for all asteroids and comets that fall into the NEO category are automatically updated at the JPL NEO Program Office. These orbits are routinely updated as new data become available. Once an orbit has been established or updated, the motion of the object is integrated forward in time to identify future Earth close approaches. Upon identifying an Earth close approach, impact probabilities are computed using both linear and non-linear techniques. The results are then posted to the Program Office web site at: http://neo.jpl.nasa.gov

Future issues regarding NEOs include the discovery of objects smaller than one kilometer for which larger aperture telescopes will be required. Objects with diameters between about 100 and one kilometer are far more numerous than the 1000 thought to be larger than one kilometer. Although a good number of these smaller objects are being discovered by the existing search programs, any short-term effort to discover and track the vast majority of these objects will require larger aperture telescopes and a far greater commitment of resources than is currently the case. In addition, a study should be conducted to outline the relative benefits of space-based detectors vs. ground-based detectors for discovering the vast (~150,000) population of NEOs that are smaller than one kilometer but still large enough to penetrate the Earth's atmosphere and cause local disasters.

Plans to internationalize the search for NEOs must continue. Particularly welcome is the upcoming inauguration of the Japanese Spaceguard center in Besei town, a facility that will add geographic diversity to the global search efforts and a much needed new telescope to the effort. The British Task Force report that was issued in September 2000 (http://www.nearearthobjects.co.uk) provided several well thought out recommendations including a call for a dedicated 3 meter class telescope for surveying substantially smaller NEOs than those currently observed by other telescopes. As a first fruit of these Task Force recommendations, the British government, in August 2001, called for proposals to establish a National Asteroid and Comet Information Centre.

Another issue that needs to be addressed in the near future is the physical characterization of NEOs. Only very modest resources are being spent upon the efforts to characterize the composition and structures of NEOs. Should an object be found upon an Earth threatening trajectory, we would need to know its mass, composition, porosity, structure, shape, and size to mount an effective mitigation strategy. At the very least, we need to increase our Earth-based and space-based observational efforts to characterize the physical nature of these objects. After all, one needs to know the enemy before dealing with it.

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